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Influence of sonication conditions on the efficiency of ultrasonic cleaning with flowing micrometer-sized air bubbles

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ABSTRACT

This paper describes the sizes of cleaned areas under different sonication conditions with the addition of flowing micrometer-sized air bubbles. The differences in the cleaned area of a glass plate pasted with silicon grease as a dirty material under different sonication conditions were investigated after tiny bubbles were blown on the dirty plate placed in an underwater sound field. The ultrasound was applied perpendicular to the bubble flow direction. The shape of the cleaned areas was nearly elliptical, so the lengths of the minor and major axes were measured. The length of the minor axis under sweep conditions (amplitude modulation), for which the average power was lower than that for continuous wave (CW) irradiation, was comparable to that for CW irradiation and was slightly larger than under bubble flow only. Not only the relatively high power for CW irradiation, but also the larger angular change of the bubble flow direction under sweep conditions contributed to the enlargement of the cleaned area in the direction of the minor axis. The combination of bubble flow and sonication under sweep or CW conditions produced a larger cleaned area compared with bubble flow only, although the increase was not higher than 20%. A rapid change from an air to water interface caused by the bubble flow and water jets caused by the collapse of bubbles due to violent pulsation is the main cleaning mechanism under a combination of ultrasound and bubble flow.

1. Introduction

The author and coworkers have previously reported that the addition of a flow of tiny bubbles (10–20 μm in diameter) produced from a mixture of compressed air and water into a 141 kHz ultrasonic field using an air-assisted atomizer can enhance sonochemical reactions, although bubble pulsation at these dimensions is transient [1]. Upon collapse, such bubbles in an ultrasonic field can potentially cause a shock wave or liquid jet, which can be used to clean a solid surface. The author and coworkers studied the yield enhancement of sonochemical reactions through the addition of particles of the appropriate size and amount [2], adjustment of the amount of dissolved gas [3,4], use of an appropriate duty cycle in pulsed operation [5], suppression of liquid surface vibrations [6,7], and the addition of tiny bubbles.

Cleaning under ultrasound with the addition of micrometer-sized bubbles has also been studied by other groups. For example, Ohno et al. observed the motion of bubbles on a surface under ultrasound irradiation at 20 kHz and 600 W using a high-speed camera, and reported that the bubbles formed clusters due to the action of secondary Bjerknes forces on a solid surface [8]. They determined that the movement of these clusters was responsible for the cleaning of the surface. Ohno et al. also found [8] that spot damage caused by ultrasonic cavitation of the sample surface did not occur in the presence of microbubbles, probably because microbubble clusters covered the sample surface. Kim et al. produced bubbles by ultrasound, and introduced them into different ultrasonic fields to clean the surface of a photomask [9]. Agarwal et al. employed this cleaning effect by ultrasonication after microbubbling for the removal of biofilms [10]. However, little is still known regarding the combination of bubbles in high-speed motion (bubble flow) from an air-assisted atomizer and ultrasonication under different conditions. Bubble flow can cause cleaning, even in the absence of ultrasound, by the impact of the gas–liquid interface on a solid surface when the bubbles collide violently with that surface. This paper describes the evaluation of the cleaned areas on dirty glass under different sonication conditions, including sweep operation (amplitude modulation) with the addition of flowing micrometer-sized air bubbles.

2. Experimental

Fig. 1(a) shows the experimental apparatus. In the experiment, a 105 kHz continuous wave (CW) or amplitude-modulated sinu-

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soidal wave signal was generated by a function generator (NF WF1946A) and amplified by a 55 dB power amplifier (ENI 1140LA). This signal was used to drive a planar piezoceramic transducer (Honda Electronics) 50 mm in diameter that was attached to a stainless-steel plate 80 mm in diameter and 1 mm thick. The electric power input to the transducer was measured using a power meter (Towa TAW-60A). Ultrasound from the driven transducer propagated through a stainless-steel plate into a $100 \times 100 \times 120\ mm^3$ (inner volume) glass tank filled with distilled water to a height of 70 mm from the bottom of the tank.

Fig. 2 shows the signal amplitude of the function-generator output in the case of amplitude modulation. The signal is a triangular wave with a minimum and maximum amplitude of a_{min} and a_{max}, respectively, and a period of T. In the present experiment, the period T was set to 1 s. The output of the power amplifier followed the cyclic changes in the signal from the function generator. In the present experiment, the maximum (a_{max}) was 0.5 V (peak to trough), while the minimum (a_{min}) was 0, 0.125, 0.25, or 0.375 V (peak to trough). These conditions are referred to below as USswp(0/4), USswp(1/4), USswp(2/4), and USswp(3/4). The continuous wave condition is referred to as UScw, and had a constant amplitude of 0.5 V (peak to trough). Lastly, the label B indicates bubble flow conditions. Sonication and bubble flow production were performed simultaneously for 60 s. A square-wave signal would have been simpler than the triangular wave, but was not used here in order to avoid sudden large increases in the voltage of the amplified signal, which could damage the transducer.

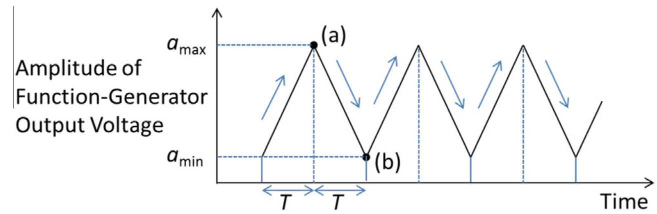

Fig. 2. Signal from function-generator for amplitude modulation of ultrasound (sweep operation).

Fig. 3 shows the distribution of the radii of bubbles radius from an air-assisted atomizer, measured in the absence of ultrasound using a particle sizer (AEROTRAC SPR 7340). The peak bubble radius was 26.5 µm, and the radius distribution ranged from approximately 13–175 µm. The present method of producing tiny air bubbles in water was based on the swirling flow of a gas–liquid mixture that the author and coworkers have described previously [1]. Using a gas–liquid mixture, Evans et al. also created bubbles with a diameter one order of magnitude smaller than their nozzle

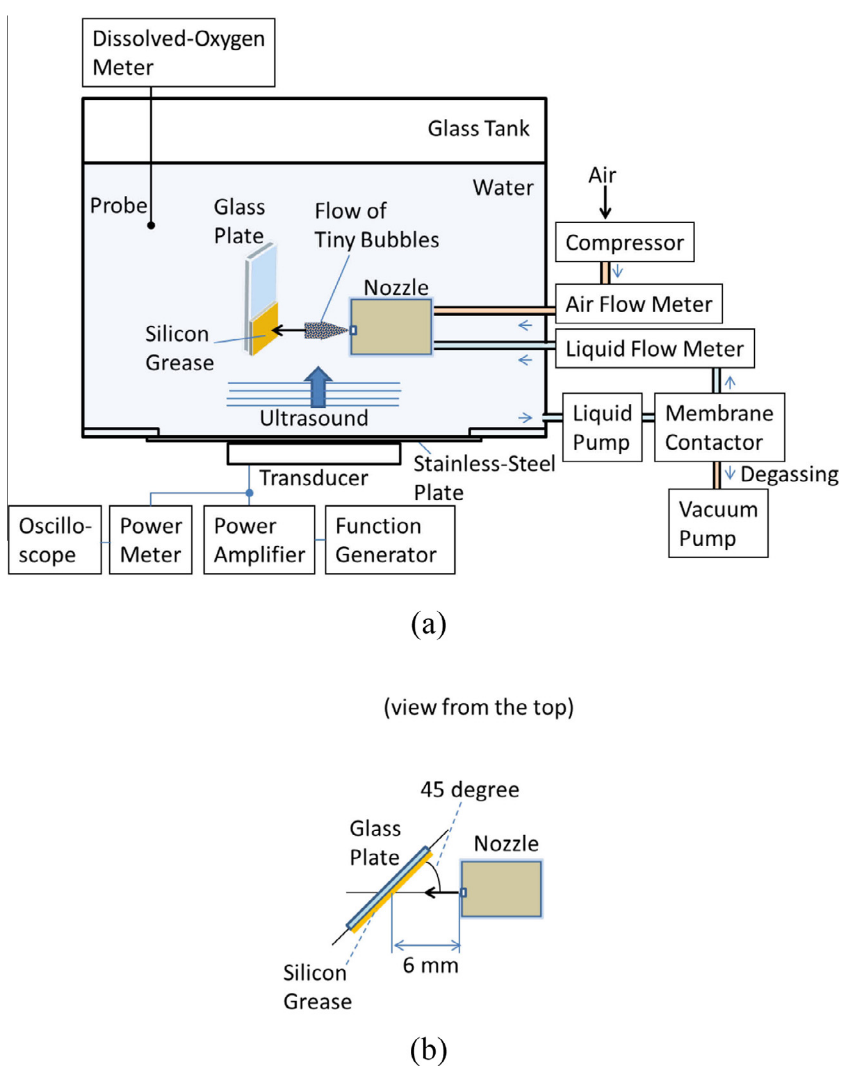

Fig. 1. (a) Experimental apparatus. (b) Arrangement of the glass plate and nozzle.